Possible Implications of Sagittarius Type Dwarf Galaxy on Microlensing Towards the Large Magellanic Cloud

HongSheng Zhao *

Max-Planck-Institute für Astrophysik, Karl-Schwarzschild-Strasse 1, 85740 Garching, Germany

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ABSTRACT

The discovery of the Sgr dwarf galaxy (Ibata, Gilmore, Irwin 1994) shows that the Galactic halo contains large clumps which are not full viralized. Stars in such a clump can lens a background extragalactic source. I use parameters of Sgr to demonstrate that microlensing by a disintegrated dwarf galaxy has a probability (optical depth) $10^{-7}-10^{-6}$, which is comparable to that of an isothermal Galactic dark halo of massive compact objects (MACHOs). This may change implications of observed microlensing events towards the LMC. If more than one such clumps are hidden in the Galactic halo, then given their enormous angular size ($\sim 5^o \times 20^o$), there is a significant chance for *any* line of sight, say the LMC direction, to intersect one of them. As an alternative to the half-MACHO dark halo models (Alcock et al. 1996a,c), I discuss a non-MACHO model with lenses of the observed events being faint stars in a hidden Sgr-like disintegrated dwarf in the line-of-sight path to the LMC.

Key words: Magellanic clouds - gravitational lensing - dark matter - Galaxy : halo - galaxies : individual (Sgr)

1 INTRODUCTION

A few dwarf galaxies are long known to orbit in the out-skirts of the Galactic halo (Irwin and Hatzidimitriou 1995 and references therein). But the recent discovery of a disintegrated dwarf galaxy at 24 kpc from us in the Sagittarius constellation (Ibata, Gilmore, Irwin 1994, 1995) shows that some of them have spiraled *in* the halo of the Galaxy. On the order of $10^{7-8}L_\odot$ luminosity of the Sgr dwarf galaxy clusters in a narrow phase space (with roughly $10\,\mathrm{km\,s^{-1}}$ velocity dispersion) and is dispersed spatially in a large faint strip probably along its orbit. Several authors have identified parts of dwarf galaxy across a large fraction of the sky (Mateo et al. 1996, Alard 1996, Alcock et al. 1996b and references therein), and its disintegrated material spans at least $5^o \times 20^o$ of the sky, which is about 16 kpc^2 in area.

It is surprising that such a "big" dwarf galaxy, which is also the nearest and probably the most luminous Galactic dwarf galaxy, has evaded previous frequent studies of the same region of the sky. The discovery naturally encourages one to speculate other dwarf galaxies accreted by the Galaxy in the past one Hubble time (Mateo 1996); they might have been torn into a strip similar to the Sgr dwarf by the tidal force of the Galaxy, and might have been missed previously because of the lack of an optimized systematic search. On

the other hand if the halo hides several of these disintegrated dwarfs, each occupying a significant solid angle of the sky, there is a fair chance for one of them showing up in deep studies of an arbitrary line of sight.

In this paper, I discuss how these hidden structures may affect the ongoing microlensing search of MACHOs, massive compact dark matter in the halo. The microlensing probability (optical depth) of an extragalactic source is determined by the density distribution of lenses along the line of sight in the halo. Most authors have used a few observed microlensing events towards the LMC to draw conclusions on the typical mass and the total mass of MACHOs (e.g. Alcock et al. 1996a,c and references therein). The results are based on the assumption that lenses in the middle range of the line of sight to the LMC are MACHOs which follow a smooth r^{-2} law of a standard isothermal halo. Here I examine the effects of a clumpy halo due to many disintegrated dwarfs in the halo.

2 LENSING BY FAINT STARS IN A SGR-LIKE DWARF GALAXY

2.1 Optical depth

In this section I compute the microlensing optical depth due to lenses in a Sgr-like dwarf galaxy. Lacking the knowledge of the real distribution of these dwarf galaxies, I will simply

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* has moved to Sterrewacht Leiden (hsz@strw.LeidenUniv.nl)

"move" Sgr dwarf galaxy in front of the LMC, and compute the microlensing probability of source stars in the LMC.

The optical depth due to lenses in the dwarf galaxy is

$$\tau_{dg} = \frac{4\pi G}{c^2} D \Upsilon \mu = 0.17 \times 10^{-6} \frac{\Upsilon}{5 M_\odot L_\odot^{-1}} \frac{\mu}{4 L_\odot \text{pc}^{-2}} \frac{D}{12\text{kpc}} \quad (1)$$

where $D = D_d \left(1 - \frac{D_d}{D_s}\right)$ is the effective distance to the dwarf galaxy, given by D_d and D_s which are the distances to the dwarf galaxy and the source. The distance to the Sgr dwarf galaxy is about $\frac{1}{2}$ of the distance to the LMC, so $D_s \approx 2D_d \approx 50$ kpc, and $D \approx 12$ kpc. μ is the surface brightness of the dwarf galaxy, which for the Sgr is $4 L_\odot pc^{-2}$ near the nucleus and is decreased to about $1.5 L_\odot pc^{-2}$ at 10° from the nucleus (Ibata et al. 1995, Mateo et al. 1995, 1996). Υ is the ratio of total mass in stars and other compact objects in the dwarf to its total stellar light. Dwarf galaxies are generally dominated by dark matter from the core to the tidal radius with Υ probably in the range $5 - 200$ (Irwin and Hatzidimitriou 1995).

The observed optical depth to the LMC is still uncertain. The number of claimed microlensing events from MACHO and EROS experiments has been fluctuating between 1 to half a dozen. Based on 6-8 events which pass their most recent selection criteria the MACHO team estimated an optical depth towards the LMC

$$\tau_{obs} = 0.17^{+0.09}_{-0.05} \times 10^{-6}; \quad (2)$$

the most recent estimation (Alcock et al. 1996c) gives a somewhat higher value.

If one interprets these events as detection of MACHOs in an isothermal Galactic dark halo, one would come to the conclusion that about 30% of the halo dark matter is in MACHOs. A full MACHO halo would give an optical depth

$$\tau_{dh} \sim \frac{V_{cir}^2}{c^2} \sim 0.5 \times 10^{-6}, \quad (3)$$

where $V_{cir} \sim 220 \, \text{km s}^{-1}$ is the amplitude of the gas rotation curve of the Galaxy, insensitive to the line-of-sight direction.

Alternatively one can use objects in a foreground Sgr-like dwarf galaxy as lenses. In the case that the dark matter in both the Galactic halo and dwarf galaxies is *non-baryonic*, lenses can only be *faint stars of the dwarf*, which depending on the shape of the mass function at the lower mass end can have a mass-to-light ratio $\Upsilon \approx (2 - 10)$. So if Sgr dwarf galaxy were "moved" in front of the LMC, then its faint stars can give an optical depth (cf. eq. 1 and 2)

$$\tau_{dg} = \left(\frac{\Upsilon}{5 M_\odot L_\odot^{-1}}\right) \tau_{obs} = (0.4 - 2) \times \tau_{obs}, \quad \Upsilon \approx (2-10).(4)$$

It may appear surprising that faint stars in a $10^{8-9} M_\odot$ *disintegrated* dwarf galaxy can produce an optical depth comparable to that of a $10^{12} M_\odot$ MACHO dark halo. The optical depth is roughly proportional to the projected density of and the distance to the lenses (cf eq. 1). A dwarf galaxy can be at a more favorable lensing distance (roughly midway to the source stars) than the MACHOs in the line of sight, which are in average at a distance about 8 kpc from us. Also the projected mass density of a dwarf galaxy, $\sim (4\Upsilon) \sim 20 M_\odot pc^{-2}$, is comparable to the MACHO halo, $\sim \left(V_{cir}^2 f_{MACHO}\right)(4\pi Gr)^{-1} \sim (100 f_{MACHO}) \sim 30 M_\odot pc^{-2}$, where f_{MACHO} is the fraction of the halo mass in MACHOs.

The above shows that stars of a foreground Sgr-like dwarf galaxy can in principle explain a significant fraction or all of the LMC microlensing events. This conclusion does *not crucially* depend on using the Sgr's surface brightness and distance at the present epoch. The optical depth reduces only by 20% if the dwarf galaxy is at 15 or 35 kpc, and by 40% at 10 or 40 kpc. The dwarf's optical depth is proportional to its surface density (cf. eq. 1), hence is a function of line-of-sight position and age. For the Sgr dwarf galaxy, the major axis gradient of the surface density is shallow: I estimate an e-folding angular size from the nucleus about 10°. A dwarf with such size is big enough to "cover" the sky area of the LMC, in which case the optical depth is insensitive to a small misalignment of the dwarf nucleus with the LMC, and the microlensing events should not strongly cluster to the LMC bar.[†] Indeed, the MACHO team observed comparable numbers of events towards the LMC bar and towards the fainter disc of the LMC. Also the optical depth of a disintegrating dwarf can even be bigger earlier on when it is less spread out and is denser; comparing to the Sgr, an undisrupted dwarf galaxy such as Fornax is much smaller and a factor of a few denser in surface density (Irwin and Hatzidimitriou 1995).

If one relaxes the model assumption to allow many compact stellar objects (such as stellar remnents and brown dwarfs) in both dwarf galaxies and the Galactic halo, then the optical depth of the dwarf can dominate that of the halo by as much as one order of magnitude (cf. eq. 4). This is because most of the gravitational mass of a dwarf galaxy can be in compact objects with a mass-to-light ratio Υ as large as $\sim 200 M_\odot L_\odot^{-1}$. Now suppose that the Galactic halo is built up by accreting 10^{3-4} MACHO-dominated dwarfs gradually without going through a violent relaxation phase. Then particles of the dwarfs are probably not fully mixed in the halo in a Hubble time, but are more likely only sheared into many strips along their orbits, similar to the situation of the Sgr dwarf. [‡] Each dwarf might cover, say a $5^o \times 20^o$ strip, which is 0.2% of the full sky. Looking through this clumpy halo the optical depth will be a wildly oscillating function of line-of-sight directions on angular scale of dwarfs. For example, an extragalactic source behind Sgr could have a much larger optical depth than a source in a line of sight offseted by a few degrees from Sgr. In this picture one can not argue any single line of sight, say the LMC, is typical with or without a dwarf in front of the LMC. It becomes problematic to constrain the distribution of MACHOs with the observed microlensing events in the LMC line-of-sight.

2.2 Event time scales and lens mass function

If the lenses of the LMC events were in a foreground dwarf galaxy rather the isothermal MACHO halo, the implications on the lens's mass would be quite different. The Einstein diameter crossing time $2t_E$ depends on the mass of the lens m, the relative transverse velocity between the lens and the

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[†] This feature is also shared by the isothermal halo model, but not by models using stars in the LMC bar as lenses (Sahu, 1994).
[‡] Such a distribution of dwarfs need not contradict the flat rotation curve of gas at large radius as long as the mass enclosed inside a radius satisfies the $M(r) \propto r$ law.

source V and the effective distance D by the following simple equation,

$$2t_E \approx 80\text{days} \left(\frac{m}{0.3M_\odot} \right)^{\frac{1}{2}} \left(\frac{D}{10\text{kpc}} \right)^{\frac{1}{2}} \left(\frac{V}{200\,\text{km s}^{-1}} \right)^{-1}. (5)$$

The 6 events recently reported by the MACHO collaboration have $2 \times t_E = 34 - 114$ days if excluding one binary event and one low confidence event (Alcock et al. 1996c). The MACHO team interpreted these events by lenses in an isothermal halo, and suggested that roughly half of the halo'mass is probably in locked up in $0.35M_\odot$ white dwarfs.

Unlike the halo lenses which have a wide range of distances and velocities, the lenses in a dwarf galaxy have negligible spread in distance and velocity. So the spread in the duration of observed events is purely due to the mass function of the dwarf lenses. The roughly factor of 3 range in the observed t_E translates to about a factor of 10 in the lens mass m. The actual median mass depends sensitively on the proper motion of the dwarf galaxy. But if I assume that the dwarf galaxy has the average velocity of the halo stars, then lens masses range between $0.1M_\odot$ to $1M_\odot$, which is plausible for an old stellar population.

3 SEARCHING FOR DISINTEGRATED DWARF GALAXIES IN THE HALO

How tight are current observational constraints on any debris of a disintegrated dwarf galaxy in front of the LMC? Such a component clearly has not been claimed in previous studies of LMC stellar populations, but can be also difficult to rule out without an optimized search of the neighboring sky region.

Stars in a dwarf galaxy are identifiable because they have a much narrow spread in distance modulus, radial velocity, and proper motion than field stars in the halo. Metal poor RR Lyraes are by far the best tracer. The Sgr dwarf galaxy is detected by RR Lyraes in many low extinction regions of the bulge, including the famous Baade window (Ibata et al. 1994, Alard 1996, Alcock et al. 1996b). Considering that stellar populations of the Galactic bulge have been studied for 50 years since Baade's (1946) pioneering discovery of variable stars in the direction, the delay of discovery is surprising and shows the limitations of previous observations. A distant disintegrated dwarf galaxy can evade detection with a combination of large size and distance, low surface density and any other foreground or background extended structure. The Sgr horizontal branch stars are spread out over many degrees of the sky with a density about 1 per square arcmin (Ibata et al. 1995) and ~ 19 magnitude in V. Their faint extended structure will not stand out in a degree size photographic plate, or a shallow color-magnitude diagram from a CCD with only arcmin field of view. Since roughly only one out of 30 RR Lyraes towards the bulge belongs to the dwarf galaxy (Alard 1996, Alcock et al. 1996b), a large deep data set of RR Lyraes is necessary, which also explains why the Sgr dwarf is discovered following the recent large kinematic surveys and OGLE, DUO and MACHO microlensing and variable star surveys towards the bulge.

The situation with the LMC is similar in many aspects except that (i) the dwarf will be in the foreground rather than background, making its RR Lyraes brighter than those in the LMC, and (ii) one is subject to mistake an extended foreground structure as parts of the very irregular structure of the LMC. Curiously the Magellanic Clouds, the Magellanic Stream, most of the known dwarf galaxies (Ursa Minor, Draco, etc.) and several remote globular clusters, and a handful of distant carbon stars (Irwin 1991 and references therein), all are dispersed on either a great circle defined by the Magellanic Stream (Lynden-Bell 1976) or a so-called Magellanic Plane (Kunkel 1979). It would be a natural speculation that an unobserved long stream of faint stars, torn from an ancient Greater Magellanic Galaxy, might also lie in such a plane with some debris in our line of sight to the LMC.

Payne-Gaposchkin (1971) published a survey of variable stars in the direction of the LMC, listing 29 short-period variables as foreground RR Lyraes with distances between 5 and 25 kpc. Interestingly 9 of these cluster at a narrow distance modulus range $16 - 17$ mag, which corresponds to a line-of-sight distance about 16 to 25 kpc. The follow-up photometric and spectroscopic studies by Connolly (1985) and Smith (1985) confirmed that most of these short-period variables are indeed foreground metal poor RR Lyraes with a radial velocity different from LMC RR Lyraes. Since only about 1 RR Lyrae between 5 to 16 kpc, and also between 16 to 25 kpc towards the LMC are expected from a smooth $r^{-3.5}$ or r^{-4} density law for the RR Lyraes in the stellar halo (Saha 1985), the 9 RR Lyraes with distance modulus $16 - 17$ mag. seem to trace a local over-density region. Whether there is a genuine excess of RR Lyraes at half of the distance to the LMC should be easily testable with large variable star data sets obtained in microlensing experiments towards the LMC.

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